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TECHNICAL REPORT BRL-TR-3058

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EPIC-2 CALCULATED IMPACT LOADING HISTORY
FOR FINITE ELEMENT ANALYSIS
OF BALLISTIC SHOCK

ENNIS F. QUIGLEY

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Although the EPIC-2 code can predict the ballistic shock environments in projectile-impacted targets, these targets must be axisymmetric. By modifying the code one can calculate the target loading history which can be used as input for a finite element analysis of the ballistic shock in normal impacted, non-axisymmetric targets. The loading history of a 20 mm fragment simulator projectile with an impact velocity of 1508 m/s on a 914 mm x 70 mm thick circular rolled homogeneous armor plate has been calculated by the EPIC-2 code and has been used in an ADINA finite element analysis of the plate. Comparisons of the EPIC-2 and ADINA response calculations show that the EPIC-2 calculated loading history can be used as loading input for finite element ballistic shock analysis. Keywords;

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I. INTRODUCTION

A series of nonperforating ballistic impact experiments[1] were conducted by the US Army Combat Systems Testing Agency (USACSTA) to characterize the ballistic shock environment in rolled homogeneous armor (rha) targets. One of these experiments involved the normal impact of a 20 mm fragment simulator projectile (fsp) on 914 mm x 914 mm x 70 mm rha plate at an impact velocity of 1508 m/s. Normal displacements were measured at radial distances of 105 mm and 241 mm from the center of the plates, and radial strains were measured at radial distances of 100 mm, 170 mm and 240 mm from the center of the plates. The EPIC-2 hydro-code[2] was used by the US Army Ballistic Research Laboratory to model these experiments and to calculate the plate's responses to impact of the fsp. Comparison[3] of the measured and EPIC-2 calculated responses (normal displacement and radial strain) showed that the EPIC-2 could calculate the response of projectile-impacted targets within the limitations of the code.

EPIC-2 is an axisymmetric code; therefore, it is limited to axisymmetric targets and to normal impacting projectiles. If, however, the EPIC-2 code is modified to calculate the projectile loading history of the target, this loading history can be used as input for a finite element analysis of ballistic shock in normal impacted, non-axisymmetric targets. This report describes the EPIC-2 calculated loading history of a 20 mm fsp with an impact velocity of 1508 m/s on a 70 mm thick rha plate, the application of this loading history in an ADINA[4] finite element analysis of the plate, and the results of the comparison of the EPIC-2 and ADINA calculations.

II. EPIC-2 CODE AND CALCULATED LOADING HISTORY

The major characteristics of the EPIC-2 code are listed in Table 1. The code performs elastic-plastic impact computations in two dimensions for axisymmetric and plane strain problems with either free or fixed boundaries. It is based on a Lagrangian finite element and lumped mass formulation in which the equations of motion are integrated directly. Nonlinear material strength and compressibility effects are included to account for elastic-plastic flow and wave propagation. The code has material descriptions for strain hardening, strain rate effects, thermal softening and failure. It uses a constant strain, triangular finite element which is well suited to represent the severe distortions occurring during high velocity impact.

The use of an axisymmetric code to model the USACSTA experiments was justified since the impact point in the experiments was the center of the plate. EPIC-2 calculations[3] had shown that the plate's response would be axisymmetric and independent of the plate's geometry and edge boundary conditions for a period of time after impact.

One of the variables calculated by the EPIC-2 code for each computational time interval was the total linear momentum of the plate. The code was modified to calculate the loading history of the projectile on the plate by calculating the time rate-of-change in the plate's total linear momentum over each computational time interval. Although the computational time interval for the impact velocity was in the order of 0.05 μs, the loading was printed out at 1.0 μs intervals.

```
+----------------------------------------------------------+
|              Table 1. EPIC-2 Code Characteristics         |
+----------------------------------------------------------+
|                                                          |
|  DISCRETIZATION:        FINITE ELEMENT METHOD            |
|                                                          |
|                         • 2D constant strain triangles   |
|                         • Lumped mass formulation        |
|                                                          |
|                                                          |
|  MESH DESCRIPTION:      LAGRANGIAN                       |
|                                                          |
|                                                          |
|  MATERIAL MODEL:        CONSTITUTIVE MODEL               |
|                                                          |
|                         • Incremental elastic-plastic    |
|                         • Von Mises yield criterion      |
|                         • Compressibility effects        |
|                         • Strain rate effects            |
|                         • Strain hardening               |
|                         • Thermal softening              |
|                                                          |
|                                                          |
|                         EQUATION OF STATE               |
|                                                          |
|                         • Mie-Gruneisen                  |
|                                                          |
|                                                          |
|  FAILURE CRITERIA:      VOLUMETRIC STRAIN                |
|                         EFFECTIVE PLASTIC STRAIN         |
|                                                          |
|                                                          |
|  POST-FAILURE MODELS:   PRESSURE CUTOFF                  |
|                         SHEAR AND TENSION FAILURE        |
|                         TOTAL FAILURE                    |
|                                                          |
+----------------------------------------------------------+
```

Figure 1 shows the computed loading history of the plate for the impact velocity of 1508 m/s. The loading has a duration time of 68 μs and a maximum peak value of 6.3 MN. For the first 30 μs the loading is very oscillatory with differences of up to 5 MN between maximum and minimum load values. There exists at 46 μs a negative loading, implying that the projectile is pulling the plate rather pushing against it. A more reasonable explanation is in terms of the dilatation wave produced by the impacting projectile. The time at which the negative loading occurs is the arrival time of the wave at the impact point after the wave's second round trip through the 70 mm thickness of the plate. Since this is a tension wave when it arrives, the plate experiences a pulling rather than a pushing.
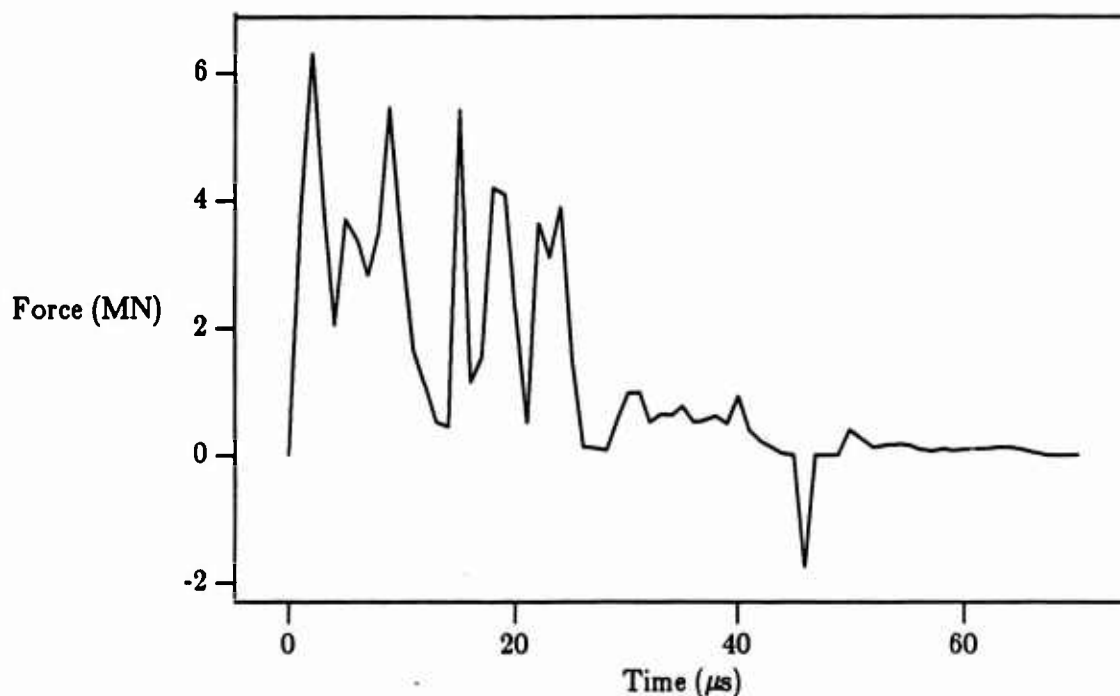
Figure 1. EPIC-2 calculated impact loading history for v_p = 1508 m/s.

III. ADINA CALCULATIONS AND EPIC-2 COMPARISONS

The ADINA finite element model of the plate is shown in Figure 2 and it is identical to the EPIC-2 model. The plate is modeled as a circular one, 914 mm in diameter and with free boundaries, and it consists of 1029 nodes and 1760 triangular elements. The horizontal and the vertical distances between the nodes are 7.62 mm and 8.67 mm, respectively. Only the first 160 mm of the plate's 457 mm radius is shown. One third of the loading shown in Figure 1 is applied to each of the top first three radial nodes as indicated in Figure 2. (The 20 mm fsp used in this experiment was completely destroyed. However, recovery of similar fsp's after lower impact velocity experiments showed the contact surface of the projectile mushroomed from a 20 mm diameter to a 33 mm diameter.)

The analysis is nonlinear, small deflection and small strain. The time integration scheme used is the Newmark method with a time step increment of 1 μs, and the equilibrium iteration method used is the full Newton with line search. The material model of the plate is bilinear elastic-plastic in which Young's modulus E = 145.1 GPa, Poisson's ratio ν = 0.275, yield stress σ_Y = 916.2 MPa, and strain hardening modulus E_T = 510.1 MPa; and the density of the plate is 7876 kg/m^3. The same material properties are used in the EPIC-2 calculations.
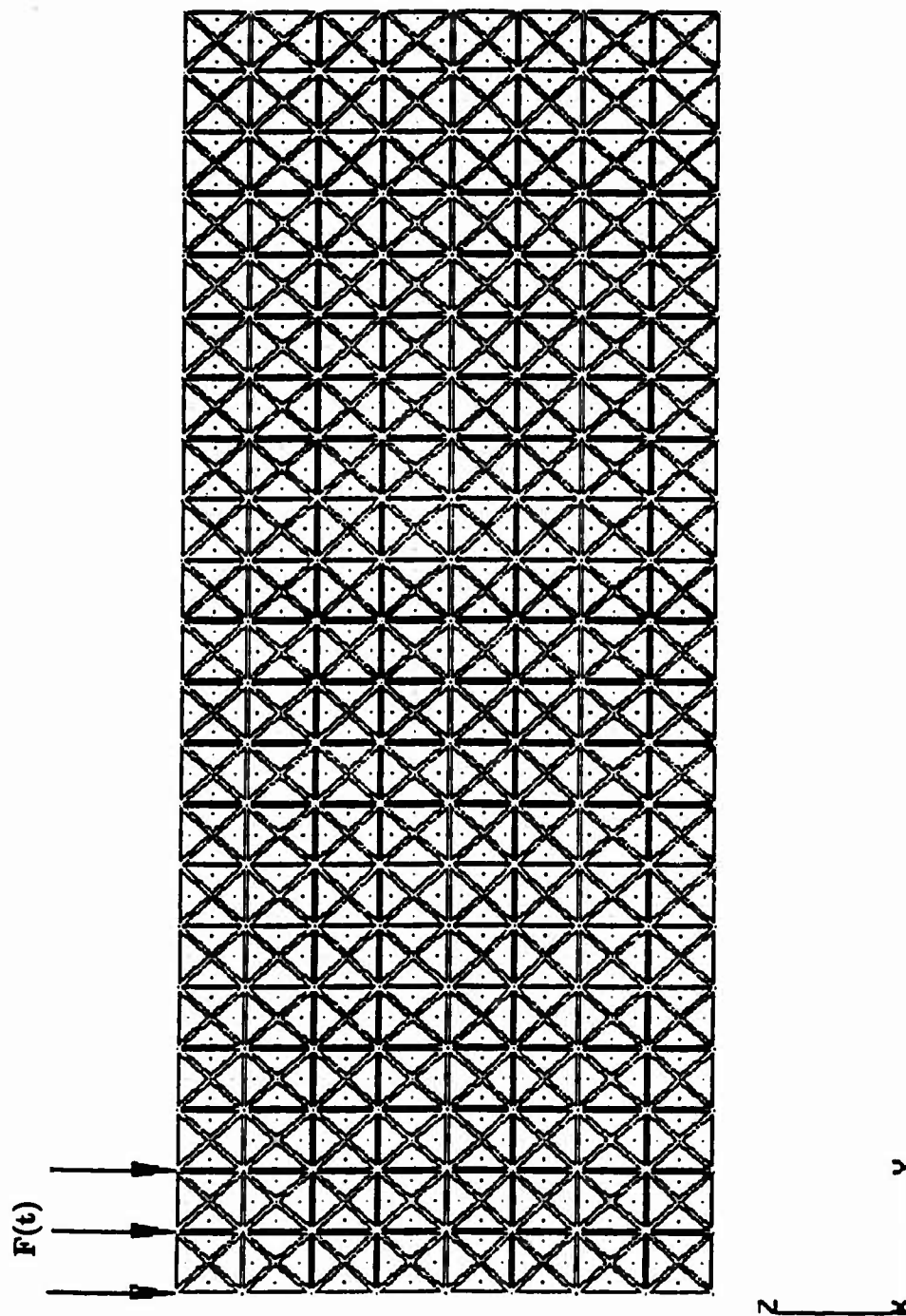
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Figure 2. ADINA finite element model of 70 mm thick plate.

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Figure 3 through 9 are plots of both the ADINA and EPIC-2 calculated responses at the same locations on the back of the plate. Figure 3 shows excellent agreement of the normal displacements at 106 mm, and Figure 4 shows good agreement of the normal displacements at 244 mm. For time $t \geq 100$ μs, the ADINA displacements are less than the EPIC-2 displacements at 244 mm. Figure 5 shows good agreement of the radial strains at 100 mm except for 50 μs $< t < 75$ μs. During this time interval the EPIC-2 maximum positive strain is approximately three times greater than the ADINA maximum positive strain. Figure 6 shows good agreement of the radial strains at 170 mm for all times. Also, it appears for $t > 250$ μs that the ADINA curve is beginning to lag behind the EPIC-2 curve. Figure 7 shows good agreement of the radial strains at 240 mm. Figure 8 shows good agreement of the normal accelerations at 106 mm for $t \lesssim 75$ μs and poor agreement for $t > 75$ μs. The ADINA positive and negative peak accelerations are much larger than the EPIC-2 peak values. Figure 9 shows good agreement of the normal accelerations at 244 mm for $t \leq 150$ μs and poor for $t > 150$ μs. Figures 10 and 11 show the ADINA and EPIC-2 primary shock spectra obtained from the normal acceleration histories shown in Figures 8 and 9. A recursive filter technique[5] is used to obtain these spectra. Figure 10 shows excellent agreement of the spectra for frequency $f \leq 50$ kHz and fair agreement for $f > 50$ kHz. Figure 11 shows excellent agreement of the spectra for $f \leq 10$ kHz, good agreement for 10 kHz $< f \leq 20$ kHz, and poor agreement for $f > 20$ kHz.

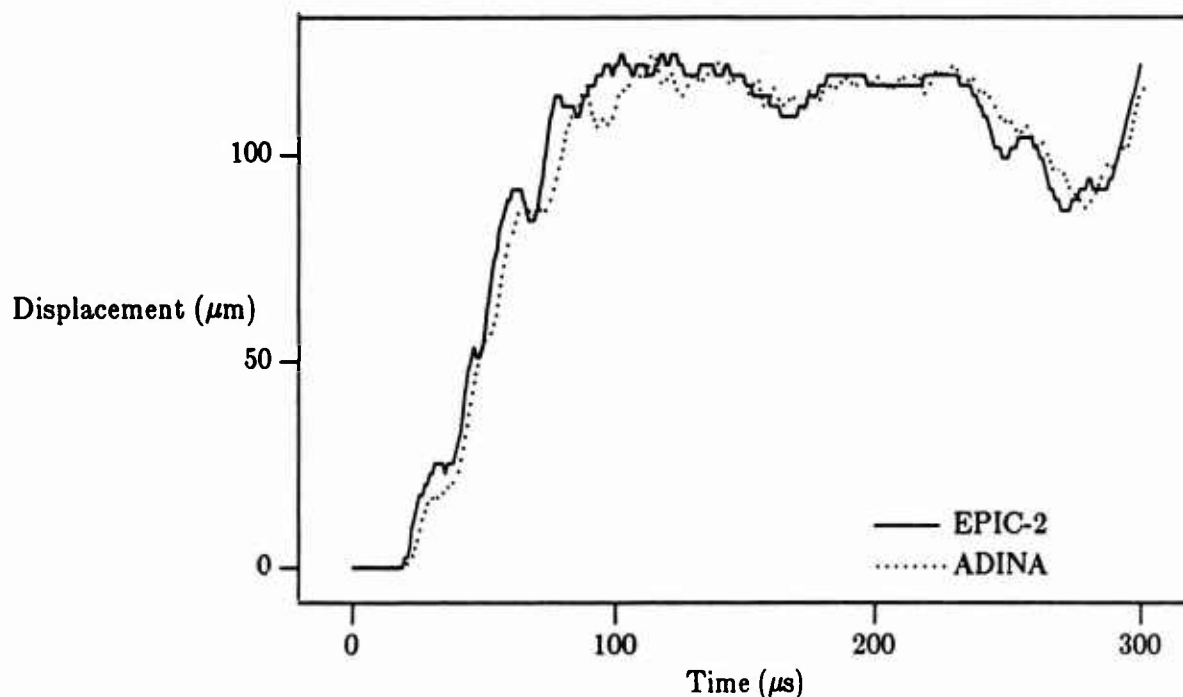Figure 3. EPIC-2 and ADINA normal displacement histories at 106 mm for $v_p = 1508$ m/s.
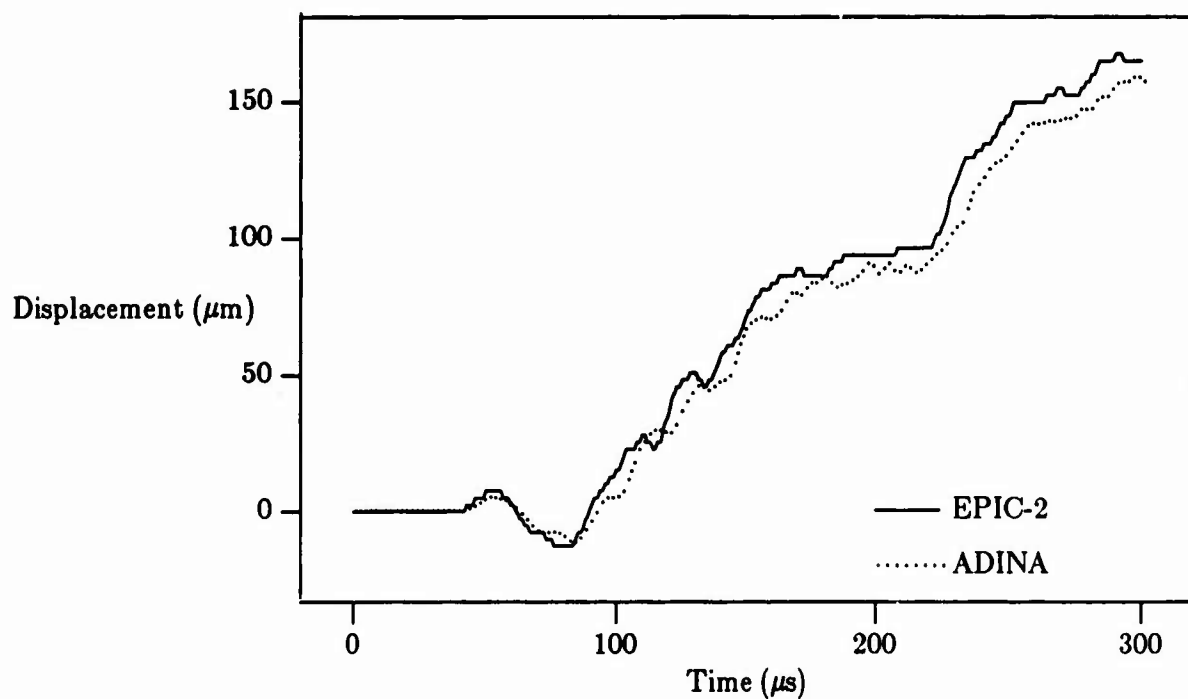
Figure 4. EPIC-2 and ADINA normal displacement histories at 244 mm for $v_p = 1508$ m/s.
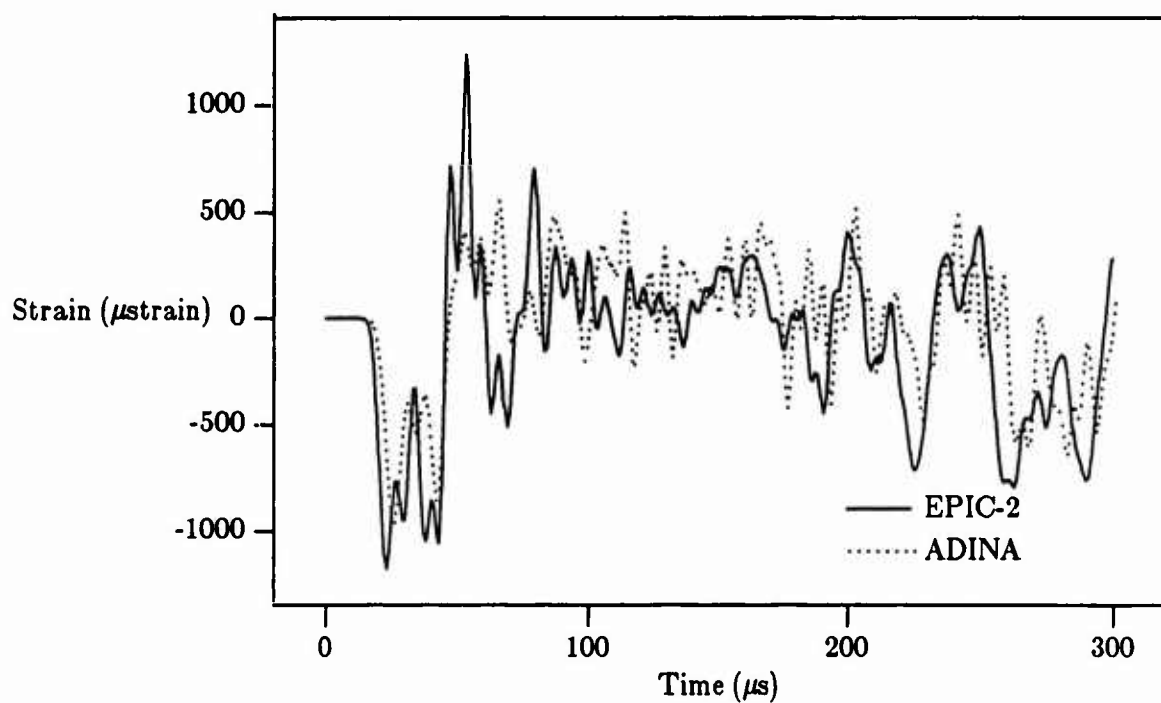

Figure 5. EPIC-2 and ADINA radial strain histories at 100 mm for $v_p = 1508$ m/s.
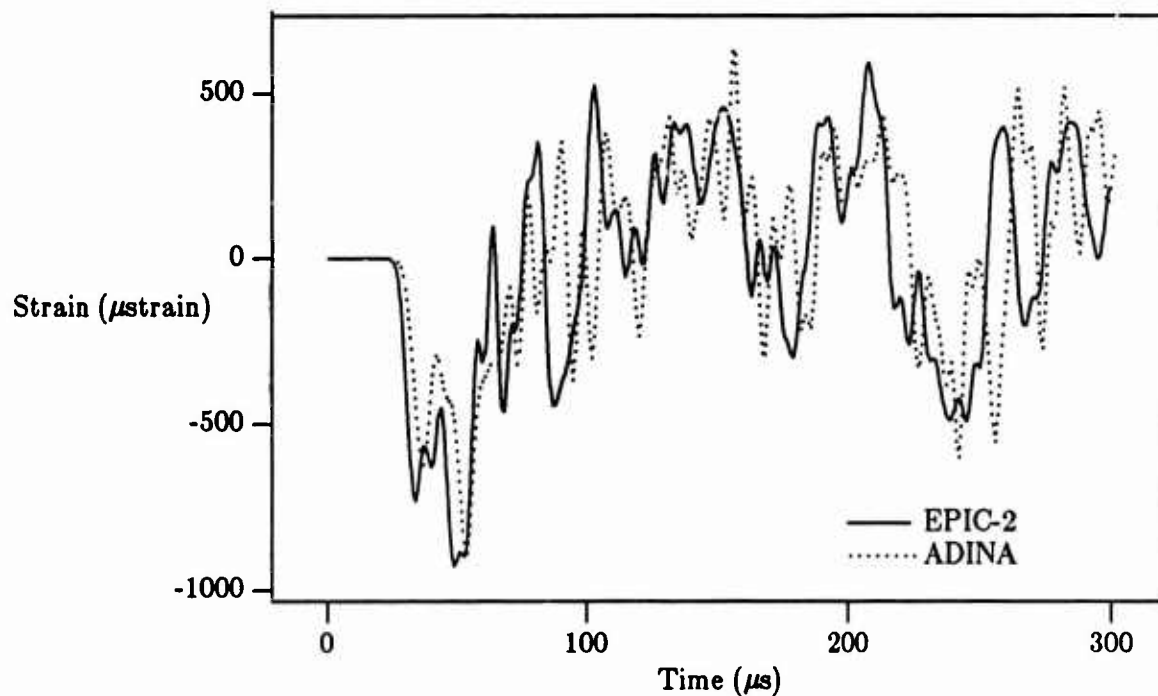
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Figure 6. EPIC-2 and ADINA radial strain histories at 170 mm for $v_p = 1508$ m/s.
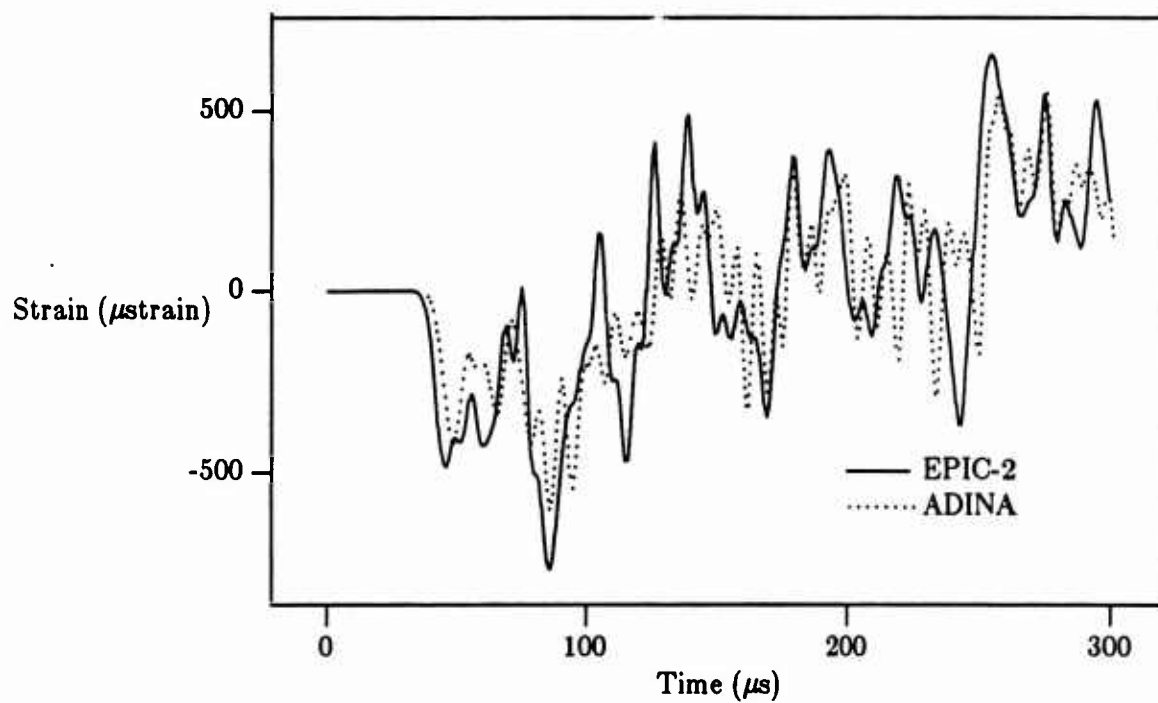

Figure 7. EPIC-2 and ADINA radial strain histories at 240 mm for $v_p = 1508$ m/s.
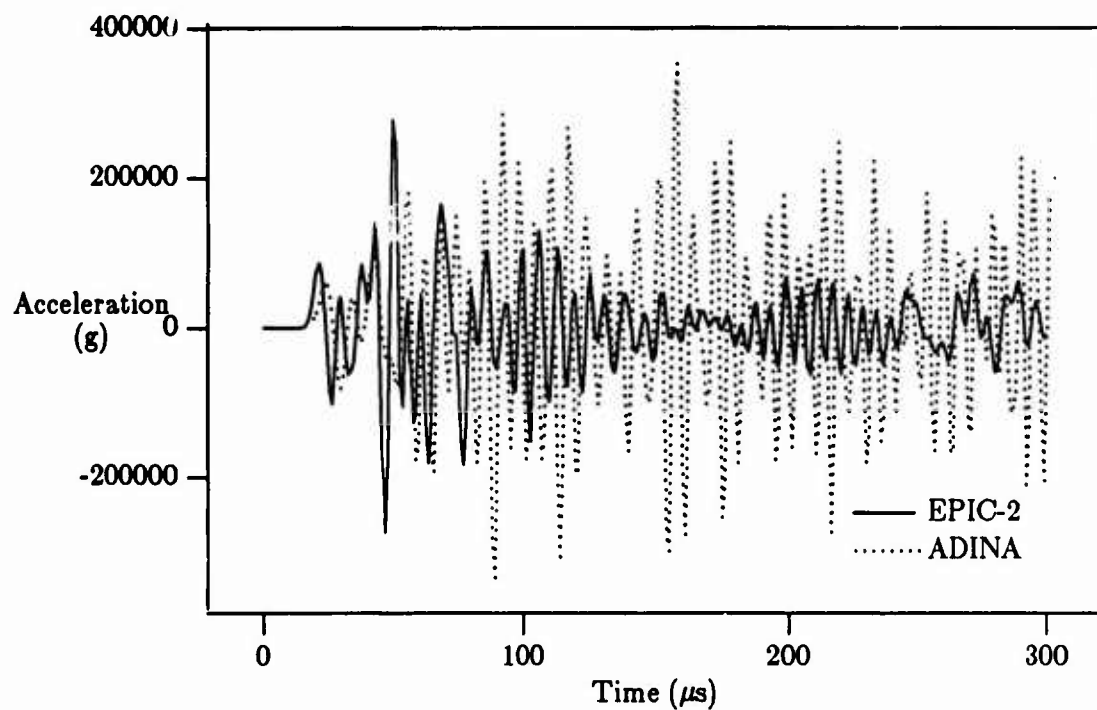
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Figure 8. EPIC-2 and ADINA normal acceleration histories at 106 mm for v_p = 1508 m/s.
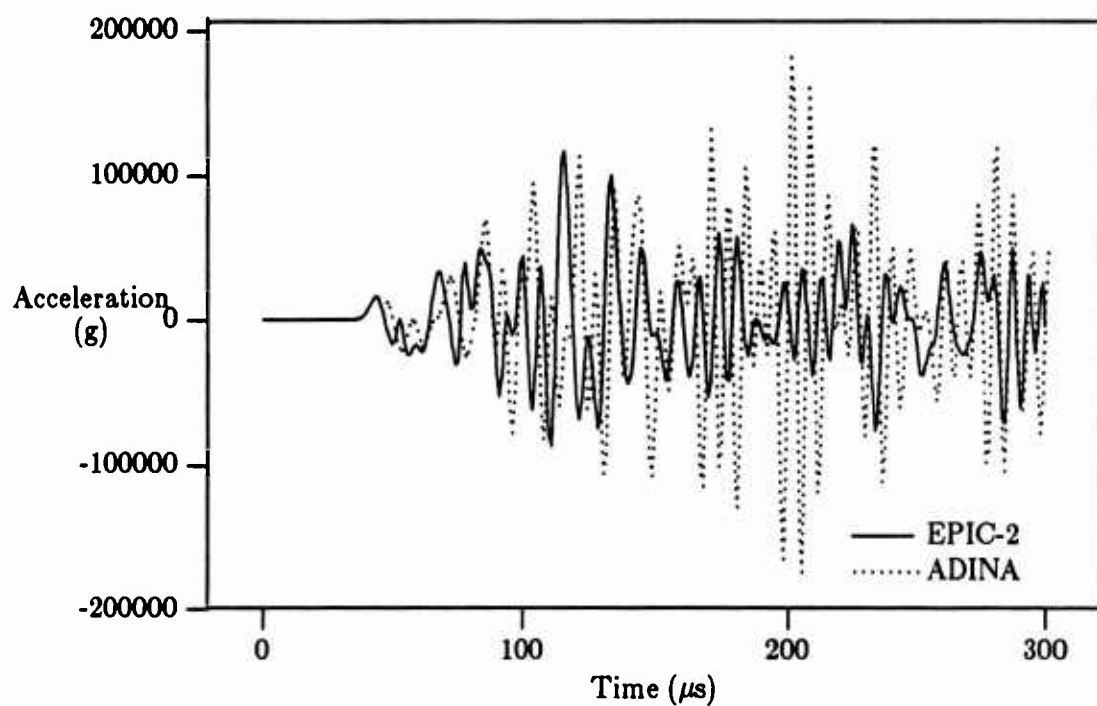

Figure 9. EPIC-2 and ADINA normal acceleration histories at 244 mm for v_p = 1508 m/s.
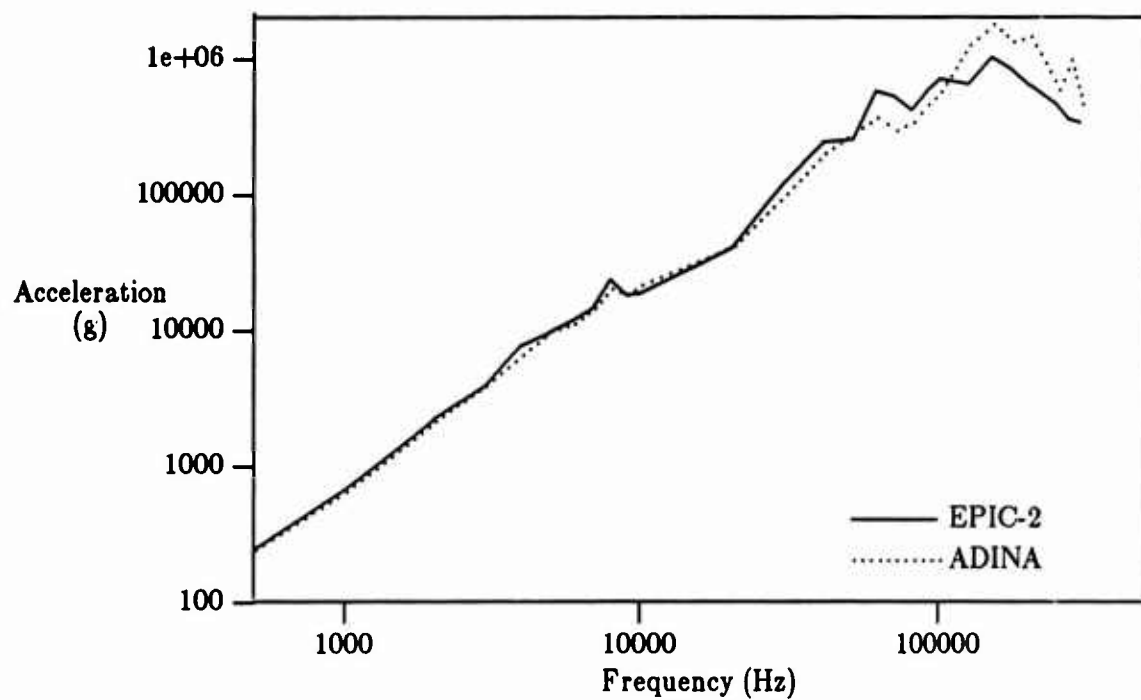
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Figure 10. EPIC-2 and ADINA primary shock spectra at 106 mm for $v_p = 1508$ m/s.
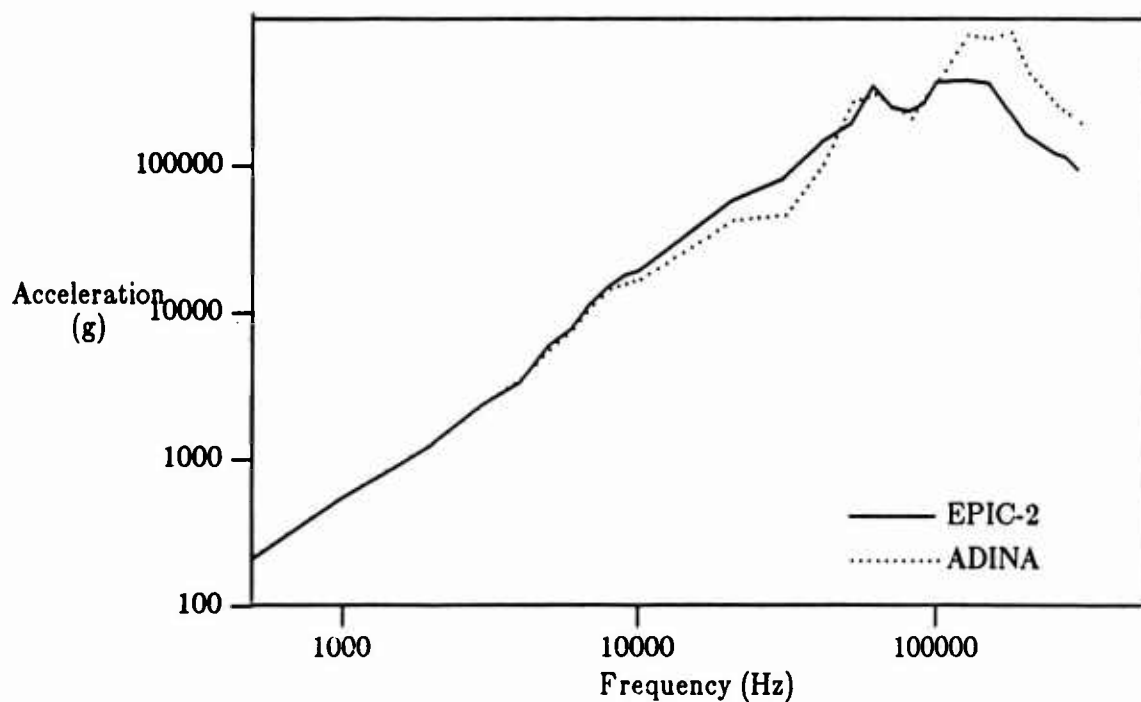
Figure 11. EPIC-2 and ADINA primary shock spectra at 244 mm for $v_p = 1508$ m/s.

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IV. SUMMARY AND CONCLUSIONS

By modifying the EPIC-2 code to calculate the time rate-of-change of the target's linear momentum, the code can calculate a loading history of an impacting projectile on the target. The loading history of a 20 mm fragment simulator projectile for an impact velocity of 1508 m/s on a 914 mm x 70 mm thick circular rolled homogeneous armor plate has been calculated by the EPIC-2 code and has been used in an ADINA finite element analysis of the plate. Comparisons of the EPIC-2 and ADINA response calculations show that the EPIC-2 calculated loading history can be used as the loading input for finite element analysis of ballistic shock.

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